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Current Status of the Sub-Angstrom Low-Voltage Electron Microscopy (SALVE) Project

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The technical realization of the spherical aberration correction in transmission electron microscopes (TEM) [1, 2] presently enables atomically-resolved analysis of electron-beam sensitive low-dimensional and low-atomic-number materials down to about 60kV. However, the maximum electron dose which the material can tolerate limits decisively the achievable specimen resolution in TEM images [3]. Low-dose modes combined with appropriate image processing techniques — in the past a domain in biological sciences — needs to be applied and developed for materials science applications [4, 5]. Using such techniques, microscopists begin to discover new physics and chemistry of low-dimensional materials on the atomic level. In the past these task have been tackled solely by means of computer simulations and analytical theory. The two-dimensional objects are very thin and have an exactly defined thickness. Therefore, their images are well suited for quantitative comparison with those obtained from image calculations. Scientists now can determine (a) the exact atomic structure of point defects [6-11], (b) the knock-on damage thresholds in 2D materials [12,13], (c) electron energy- and dose-dependent structural rearrangements of defects from atomically resolved image sequences [14,15], (d) bonding effects information in high-resolution TEM images of covalently bonded light elements [16], (e) the structure of grain boundaries and dislocations and their dynamics [17-22], (f) new transformation routes between carbon nanostructures [23-25], and moreover (g) the structure of the two-dimensional amorphous phase on the atom-by-atom base [26, 27]. Above 80kV, the low intrinsic contrast and the high susceptibility of these materials to electron-beam induced knock-on damage prevents an atomically resolved analysis,

Recent low-voltage microscope developments address electron energies down to 40keV [28], 30keV [29], or 20keV [30] because materials, in particular low-Z materials, often require imaging at energies appreciably lower than 80keV or 60keV. To obtain high image contrast and high resolution at these low energies, it is mandatory to compensate for the spherical aberration and the chromatic aberration of the objective lens [31]. We demonstrate by means of image calculations [32, 33] at 20keV and 40keV that in the case of spherical and chromatic correction the image contrast cannot be described by means of the weak phase-object approximation, even not even for graphene, a mono-atomic layer of carbon atoms. Because at these voltages all atoms are strong scatters, we must incorporate the effect of inelastic scattering in the image simulation of low-*Z* specimens because the inelastic scattering cross-section is about 20/Z times the elastic scattering cross-section. We show first results for simulated energy-filtered elastic and inelastic images of graphene and silicon [33]. The new Cc/Cs-corrector has been successfully installed into the SALVE microscope and we will show first results from this voltage-tuneable microscope (20-80kV (120kV)). We will discuss the motivation for flexibility in voltage-tuning by means of the complexity of beam-sample interactions in calcite [34] and metal-filled single-walled carbon nanotubes [35].

Apart from high-resolution imaging, we take advantage of the exceptionally low background noise of the SALVE microscopy at low voltages enabling the investigation of plasmons in single [36] and multi-layer graphene using angle-resolved electron energy loss spectroscopy [37]. In addition, we show that graphene can now serve as an extreme thermal platform for physisorbed carbon species whose transformations can be imaged under the influence of Joule heat and electron irradiation atom-by-atom [38]. Finally, we use graphene and carbon nanotubes as substrates for radiation-sensitive compounds [39].

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